

# Dark matter with photons

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**Abstract.** If the present dark matter in the Universe annihilates into Standard Model particles, it must contribute to the gamma ray fluxes detected on the Earth. The magnitude of such contribution depends on the particular dark matter candidate, but certain features of the produced spectra may be analyzed in a rather model-independent fashion. In this communication we briefly revise the complete photon spectra coming from WIMP annihilation into Standard Model particle-antiparticle pairs obtained by extensive Monte Carlo simulations and consequent fitting functions presented by Dombriz et *al.* in a wide range of WIMP masses. In order to illustrate the usefulness of these fitting functions, we mention how these results may be applied to the so-called brane-world theories whose fluctuations, the branons, behave as WIMPs and therefore may spontaneously annihilate in SM particles. The subsequent  $\gamma$ -rays signal in the framework of dark matter indirect searches from Milky Way dSphs and Galactic Center may provide first evidences for this scenario.

## 1. Introduction

According to present observations of large scale structures, CMB anisotropies and light nuclei abundances, dark matter (DM) cannot be accommodated within the Standard model (SM) of elementary particles. Indeed, DM presence is a required component on cosmological scales, but also to provide a satisfactory description of rotational speeds of galaxies, orbital velocities of galaxies in clusters, gravitational lensing of background objects by galaxy clusters and the temperature distribution of hot gas in galaxies and clusters of galaxies. The experimental determination of the DM nature will require the interplay of collider experiments and astrophysical observations. These searches use to be classified in direct or indirect searches (see [1] and references in Introduction of [2]). Concerning direct ones, the elastic scattering of DM particles from nuclei should lead directly to observable nuclear recoil signatures although the weak interactions between DM and the standard matter makes DM direct detection difficult.

On the other hand, DM might be detected indirectly, by observing their annihilation products into SM particles. Thus, even if WIMPs (Weakly Interacting Massive Particles) are stable, two of them may annihilate into ordinary matter such as quarks, leptons and gauge bosons. Their annihilation in different places (galactic halo, Sun, etc.) produce cosmic rays to be discriminated through distinctive signatures from the background. After WIMPs annihilation a cascade process occurs. In the end the stable particles: neutrinos, gamma rays, antimatter... may be observed

through different devices. Neutrinos and gamma rays have the advantage of maintaining their original direction due to their null electric charges.

This communication precisely focuses on photon production coming from WIMPs when they annihilate into SM particles. Photon fluxes in specific DM models are usually obtained by software packages such as DarkSUSY and micrOMEGAs based on PYTHIA Monte Carlo event generator [3] after having fixed a WIMP mass for the particular SUSY model under consideration. In this sense, the aim of this investigation is to provide fitting functions for the photon spectra corresponding to each individual SM annihilation channel and, in addition, determine the dependence of such spectra on the WIMP mass in a model independent way. This would allow to apply the results to alternative DM candidates for which software packages have not been developed. On the other hand, the information about channel contribution and mass dependence can be very useful in order to identify gamma-ray signals for specific WIMP candidates and may also provide relevant information about the photon energy distribution when SM pairs annihilate.

The paper is organized as follows: in section 2, we review the standard procedure for the calculation of gamma-ray fluxes coming from WIMP pair annihilations. Section 3 is then devoted to the details of spectra simulations performed with PYTHIA. We mention here some important issues about the final state radiation and the particular case of the top quark annihilation channel. In section 4, we introduce the fitting formulas used to describe the spectra depending upon the annihilation channel. Then, in section 5 we explicitly provide the results for two relevant annihilation channels. Section 6 is finally devoted to describe how these results may be useful in brane-world theories providing WIMP candidates.

## 2. Gamma-ray flux from DM annihilation

Let us remind that the  $\gamma$ -ray flux from the annihilation of two WIMPs of mass  $M$  into two SM particles coming from all possible annihilation channels (labelled by the subindex  $i$ ) is given by:

$$\frac{d\Phi_{\gamma}^{\text{DM}}}{dE_{\gamma}} = \underbrace{\frac{1}{4\pi M^2} \sum_i \langle \sigma_i v \rangle \frac{dN_{\gamma}^i}{dE_{\gamma}}}_{\text{Particle model dependent}} \times \underbrace{\frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{\text{l.o.s.}} \rho^2[r(s)] ds}_{\text{Dark matter density dependent}}, \quad (1)$$

where  $M$  denotes the mass of the WIMP,  $\langle \sigma_i v \rangle$  holds for the thermal averaged annihilation cross-section of two WIMPs into two ( $i^{\text{th}}$  channel) SM particles and  $\rho$  is the DM density.

The first piece of the r.h.s. in (1) depends upon the particular particle physics model for DM annihilations. In particular, the self-annihilation cross sections are mainly described by the theory explaining the WIMP physics, whereas the number of photons produced in each decaying channel per energy interval involves decays and/or hadronization of unstable products, for instance quarks and gauge bosons. Consequently, the detailed study of these decay chains and non-perturbative effects related to QCD is an almost impossible task to be tackled by any analytical approach. The second piece in (1) is a line-of-sight (l.o.s.) integration through the DM density distribution of the target and averaged over the detector solid angle  $\Delta\Omega$ . Let us discuss each of these pieces separately:

### 2.1. Particle Physics model

Although annihilation cross sections are not known, they are restricted by collider constraints and direct detection. In addition, the thermal relic density in the range  $\Omega_{\text{CDM}} h^2 = 0.1123 \pm 0.0035$  which is determined by fitting the standard  $\Lambda$ CDM model to the WMAP7 data [4], the latest measurements from the BAO in the distribution of galaxies [5] and the Hubble constant measurement [6], do not allow arbitrary contributions from the DM gamma ray fluxes.

As already mentioned, the annihilation of WIMPs is closely related to SM particle production. The time scale of annihilation processes is shorter than typical astrophysical scales. This fact implies that only stable or very long-lived particles survive to the WIMP annihilations and may therefore be observed by detectors.

For most of the DM candidates, the production of mono-energetic photons is very suppressed. The main reason for such a suppression comes from the fact that DM is neutral. Therefore, the gamma-ray signal comes fundamentally from secondary photons originated in the cascade of decays of gauge bosons and jets produced from WIMP annihilations. These annihilations would produce in the end a broad energy distribution of photons, which would be difficult to be distinguished from the background. However, the directional dependence of the gamma ray intensity coming from these annihilations is mainly localized in point-like sources which may provide a distinctive signature.

All those channels contributions produce a broad energy gamma ray flux, whose maximum constitutes a potential signature for its detection. On the other hand, a different strategy can be followed by taking into account the fact that the cosmic ray background is suppressed at high energies. Primary photons coming from the Weicksäcker-Williams radiation dominate the spectrum at energies close to the mass of the DM candidate and their signature is potentially observable as a cut-off [7]. This approach is less sensitive to electroweak corrections which may be important if the mass of the DM candidate is larger than the electroweak scale [8].

## 2.2. DM density directionality

The line of sight integration can be obtained from:

$$\langle J \rangle_{\Delta\Omega} \doteq \frac{1}{\Delta\Omega} \int_{\Delta\Omega} J(\psi) d\Omega = \frac{2\pi}{\Delta\Omega} \int_0^{\theta_{\max}} d\theta \sin\theta \int_{s_{\min}}^{s_{\max}} ds \rho^2 \left( \sqrt{s^2 + s_0^2 - 2ss_0 \cos\theta} \right) \quad (2)$$

where  $J(\psi) = \int_{\text{l.o.s.}} ds \rho^2(r)$ . The angled brackets denote the averaging over the solid angle  $\Delta\Omega$ , and  $s_{\min}$  and  $s_{\max}$  are the lower and upper limits of the line-of-sight integration:  $s_0 \cos\theta \pm \sqrt{r_t^2 - s_0^2 \sin^2\theta}$ . In this formula  $s_0$  is the heliocentric distance and  $r_t$  is the tidal radius.

Traditionally, the galactic center has attracted the attention of this type of directional analysis since standard cusped Navarro-Frenk-White halos predict the existence of a very important amount of DM in that direction [9]. However, this assumption is in contradiction with a substantial body of astrophysical evidences [10], and a core profile is not sensitive to standard DM candidates. On the contrary, cusped profiles are not excluded for the Local Group dwarf spheroidals (dSphs) that constitute interesting targets since they are much more dominated by DM. In this way, directional analysis towards Canis Major, Draco and Sagittarius or Segue 1 [11] are more promising.

In any case, galaxy clusters are also promising targets [12]. Other alternative strategy takes advantage of the large field of view of FERMI, that may be sensitive to the continuum photon flux coming from DM annihilation at moderate latitudes ( $|b| > 10^\circ$ ) [9]. Other proposed targets, as the Large Magellanic Cloud [13], are less interesting since their central parts are dominated by baryonic matter.

## 3. Procedure

In this section, we explicitly specify how gamma rays spectra have been generated and we will discuss some issues concerning the final state radiation and the top quark channel particularities.

### 3.1. Spectra generation

Throughout this investigation, we have used the particle physics PYTHIA software [3] to obtain our results. The WIMP annihilation is usually split into two separated processes: The first

describes the annihilation of WIMPs and its SM output. The second one considers the evolution of the obtained SM unstable products. Due to the expected velocity dispersion of DM, most of the annihilations happen quasi-statically. This fact allows to state that by considering different center of mass (CM) energies for the obtained SM particles pairs from WIMP annihilation process, we are indeed studying different WIMP masses, i.e.  $E_{\text{CM}} \simeq 2M$ . The procedure to obtain the photon spectra is thus straightforward: For a given pair of SM particles which are produced in the WIMP annihilation, we count the produced number of photons. Statistics have to be large enough, in particular for highly energetic photons usually suppressed when not high enough number of annihilations is simulated.

### 3.2. Final State Radiation

If the final state in the annihilation process contains charged particles, there is a finite probability of emission of an additional photon [14]. In principle there are two types of contributions: that coming from photons directly radiated from the external legs, which is the final state radiation we have considered in the work, and that coming from virtual particles exchanged in the WIMP annihilation process. The first kind of contribution can be described for relativistic final states by means of an universal Weizsäcker-Williams term fundamentally independent from the particle physics model [14]. On the other hand, radiation from virtual particles only takes place in certain DM models and is only relevant in particular cases, for instance, when the virtual particle mass is almost degenerate with the WIMP mass. Even in these cases, it has been shown [15] that although this effect has to be included for the complete evaluation of fluxes of high energy photons from WIMP annihilation, its contribution is relevant only in models and at energies where the lines contribution is dominant over the secondary photons. For those reasons and since the aim of the present work is to provide model independent results for photon spectra, only final state radiation was included in our simulations.

### 3.3. The case for $t$ quark decay

The decay of top ( $t$ ) quark is not explicitly included in PYTHIA package. We have approximated this process by its dominant SM decay, i.e. each (anti) top decays into  $W^{+(-)}$  and (anti) bottom. In order to maintain any non-perturbative effect, we work on an initial four-particle state composed by  $W^+b$  coming from the top and  $W^-\bar{b}$  from anti-top, which keeps all kinematics and color properties from the original pair. Starting from this configuration, we have forced decays and hadronization processes to evolve as PYTHIA does and therefore, the gamma rays spectra corresponding to this channel have also been included in our analysis.

In order to verify the validity of these results, further calculations were made [16] by including hadronic string between  $b\bar{b}$  and improving statistics in the high energy photons range. Conclusions about  $t$  quark channel remained unchanged with respect to the ones in [2].

## 4. Analytical fits to PYTHIA simulation spectra

In this section we present the fitting functions used for the different channels. According to the PYTHIA simulations described in the previous section, three different parametrizations were required in order to fit all available data from the studied channels: one for quarks (except top quark) and leptons, a second one for  $W$  and  $Z$  gauge bosons and a third one for top quark.

The parameters in the following expressions were considered in principle to be WIMP mass dependent and their mass dependences were fitted by using power laws.

#### 4.1. Quarks and leptons

For quarks (except the top),  $\tau$  and  $\mu$  leptons, the most general formula needed to reproduce the behavior of the differential number of photons per photon energy may be written as:

$$x^{1.5} \frac{dN_\gamma}{dx} = a_1 \exp \left( -b_1 x^{n_1} - b_2 x^{n_2} - \frac{c_1}{x^{d_1}} + \frac{c_2}{x^{d_2}} \right) + q x^{1.5} \ln [p(1-x)] \frac{x^2 - 2x + 2}{x} \quad (3)$$

In this formula, the logarithmic term takes into account the final state radiation through the Weizsäcker-Williams expression [17, 14]. Nevertheless, initial radiation is removed from our Monte Carlo simulations in order to avoid wrongly counting their possible contributions.

Strictly speaking, the  $p$  parameter in the Weizsäcker-Williams term in the previous formula is  $(M/m_{particle})^2$  where  $m_{particle}$  is the mass of the charged particle that emits radiation. However in our case, it will be a free parameter to be fitted since the radiation comes from many possible charged particles, which are produced along the decay and hadronization processes. Therefore we are encapsulating all the bremsstrahlung effects in a single Weizsäcker-Williams-like term.

Concerning the  $\mu$  lepton, the expression above (3) becomes simpler since the exponential contribution is absent. Thus its flux becomes

$$x^{1.5} \frac{dN_\gamma}{dx} = q x^{1.5} \ln [p(1-x^l)] \frac{x^2 - 2x + 2}{x} \quad (4)$$

where the  $l$  parameter in the logarithm is needed in order to fit the simulations as will be seen in the corresponding sections.

Parameters in expression (3) are channel dependent as can be found in [2]. Depending on the studied channel, these parameters may be either dependent or independent from the studied WIMP mass. For instance, the case for  $c$  quark was studied in [18].

#### 4.2. $W$ and $Z$ bosons

For the  $W$  and  $Z$  gauge bosons, the parametrization used to fit the Monte Carlo simulation is:

$$x^{1.5} \frac{dN_\gamma}{dx} = a_1 \exp \left( -b_1 x^{n_1} - \frac{c_1}{x^{d_1}} \right) \left\{ \frac{\ln[p(j-x)]}{\ln p} \right\}^q \quad (5)$$

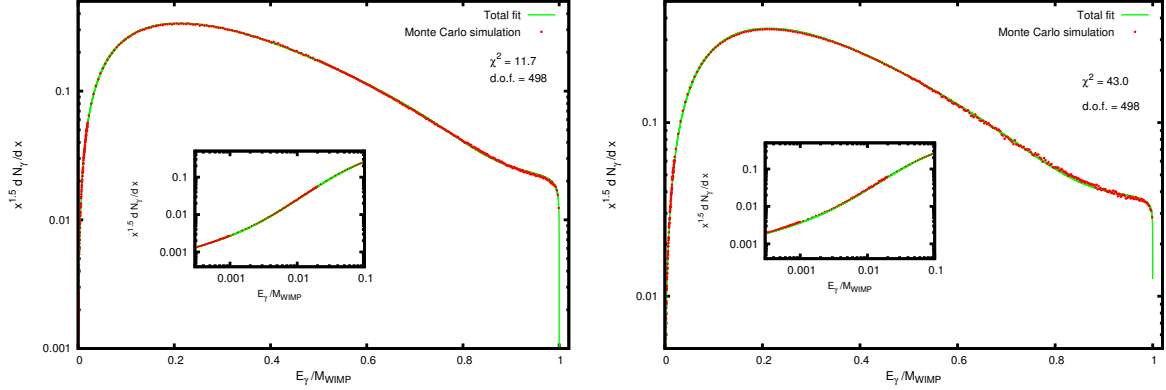
This expression differs from the expression (3) in the absence of the additive logarithmic contribution. Nonetheless, this contribution acquires a multiplicative character. The exponential contribution is also quite simplified with only one positive and one negative power laws. Moreover,  $a_1$ ,  $n_1$  and  $q$  parameters appear to be independent of the WIMP mass. The rest of parameters, i.e.,  $b_1$ ,  $c_1$ ,  $d_1$ ,  $p$  and  $j$ , are WIMP mass dependent and were determined in [2] for each WIMP mass and for the  $W$  and  $Z$  separately. In both cases the covered WIMP mass range was from 100 to  $10^4$  GeV. Nonetheless, for masses higher than 1000 GeV, no significant change in the photon spectra for both particles [2] was observed.

#### 4.3. $t$ quark

Finally, for the top channel, the required parametrization turned out to be:

$$x^{1.5} \frac{dN_\gamma}{dx} = a_1 \exp \left( -b_1 x^{n_1} - \frac{c_1}{x^{d_1}} - \frac{c_2}{x^{d_2}} \right) \left\{ \frac{\ln[p(1-x^l)]}{\ln p} \right\}^q \quad (6)$$

Likewise the previous case for  $W$  and  $Z$  bosons, gamma-ray spectra parametrization for the top is quite different from that given by expression (3). This time, the exponential contribution is more complicated than the one in expression (5), with one positive and two negative power laws.



**Figure 1.** Photon spectra for two WIMP masses (1000 GeV and 50 TeV) in the  $\tau^+\tau^-$  annihilation channel. Red dotted points are PYTHIA simulations and solid lines correspond to the proposed fitting functions.

Again, the additive logarithmic contribution is absent but it acquires a multiplicative behavior. Notice the exponent  $l$  in the logarithmic argument, which is required to provide correct fits for this particle. Moreover,  $a_1$ ,  $c_1$ ,  $d_1$  and  $d_2$  parameters appear to be independent of the WIMP mass. The rest of parameters, i.e.,  $b_1$ ,  $n_1$ ,  $c_2$ ,  $p$ ,  $q$  and  $j$ , are WIMP mass dependent and were determined in [2]. The covered WIMP mass range for the top case was from 200 to  $10^5$  GeV. Nevertheless, at masses higher than 1000 GeV it was observed again [2] that there is no significant change in the gamma-ray spectra. Consistency of this result was verified in [16].

## 5. Some results: $\tau$ lepton and $t$ quark

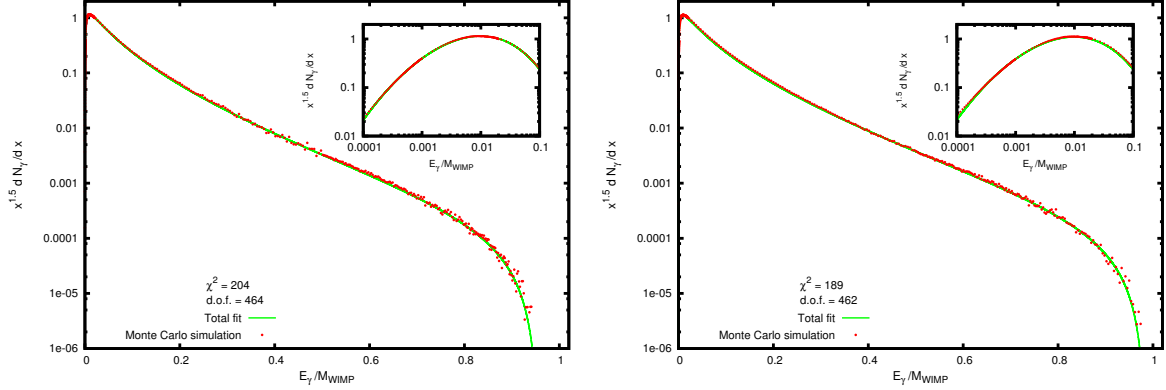
In order to illustrate the explained procedure, we present here some representative annihilation channels:  $\tau$  lepton and  $t$  quark.

For  $\tau$  lepton channel the studied mass range was from 25 GeV to 50 TeV. The mass dependent parameters in expression (3) are only  $n_1$  and  $p$  whereas  $a_1$ ,  $b_1$ ,  $b_2$ ,  $n_2$ ,  $c_1$ ,  $d_1$ ,  $c_2$ ,  $d_2$  and  $q$  are mass independent. Figure 1 presents  $\tau$  channel spectra for 1 and 50 TeV WIMP masses.

Finally, for  $t$  quark channel the studied mass range was from 200 GeV to 10 TeV although the spectra are the same from 1 GeV onwards. The mass dependent parameters in expression (6) are  $b_1$ ,  $n_1$ ,  $c_2$ ,  $p$ ,  $q$  and  $l$  whereas  $a_1$ ,  $c_1$ ,  $d_1$  and  $d_2$  are mass independent. Figure 2 presents  $t$  channel spectra for two different WIMP masses, 500 and 1000 GeV.

## 6. Brane-world theory as an example

It has been suggested that our universe could be a 3-dimensional brane where the SM fields live embedded in a D-dimensional space-time. In flexible braneworlds, in addition to the SM fields, new degrees of freedom appear on the brane associated to brane fluctuations, that is the branons. In brane-world models with low tension, branons appear to be massive and weakly interacting fields, so natural candidates to DM [19, 20, 21]. Therefore, their annihilations by pairs may produce SM particles and gamma photons by the subsequent processes of hadronization and decay. Limits on the model parameters, the WIMPs mass  $M$  and the tension scale  $f$ , are given both from collider experiments and indirect search of DM. In particular, the self-annihilation cross section of branons depends on the two parameters of the model [19, 22]. In the case of heavy branons, neglecting three body annihilations and direct production of two photons, the main contribution to the photon flux comes from branon annihilation into  $ZZ$  and  $W^+W^-$  (see



**Figure 2.** Photon spectra for two WIMP masses (500 and 1000 GeV) in the  $t\bar{t}$  annihilation channel. Red dotted points are PYTHIA simulations and solid lines correspond to the proposed fitting functions.

Figure 1 in [23]) according to the expression

$$\langle \sigma_{Z,W} v \rangle = \frac{M^2 \sqrt{1 - \left(\frac{m_{Z,W}}{M}\right)^2} (4M^4 - 4M^2 m_{Z,W}^2 + 3m_{Z,W}^4)}{64f^8\pi^2}. \quad (7)$$

The contribution from heavy fermions, i.e. annihilation in  $t\bar{t}$  channel, can be shown to be subdominant [24]. Therefore, expression (7) represents the self-annihilation cross section to be considered in (1) for the study of these theories.

The astrophysical part of (1) depends as already mentioned on both the performed experiment and DM profile of the source.  $\langle J \rangle_{\Delta\Omega}$  value is approximately  $10^{23} \text{ GeV}^2 \text{ cm}^{-5} \text{ sr}^{-1}$  for dSphs galaxy, but strongly dependent also from the distance of the source for a given DM profile. The technical details of the different experiments and the value of the background also affect the minimum detectable gamma ray flux. The minimum expected value of this flux as coming from a given source and instrument may be given by the following expression

$$\frac{\Phi_\gamma \sqrt{\Delta\Omega A_{eff} t}}{\sqrt{\Phi_\gamma + \Phi_{Bg}}} \geq 5, \quad (8)$$

By integrating expression (1) over the energy threshold of the selected device, an estimation of  $N_\gamma < \sigma v >$  can be found and matched with the expected one [23] depending on the theoretical model. This procedure allows to select the most promising target to be investigated with current ground-based or satellites experiments (MAGIC [25], EGRET [26], FERMI [27]) or with a new generation of them (CTAs [28]). Refer to [23] for further details.

## 7. Conclusions

We have presented the model-independent fitting functions for the photon spectra coming from WIMPs pair annihilation into Standard Model particle-antiparticle pairs for all the phenomenologically relevant channels. This analysis is model independent and therefore, provided a theoretical model our formulas make it possible to obtain the expected photon spectrum in a relatively simple way. Explicit calculations for all studied channels [2] are available at the websites [29] and [30].

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